Mesoscale Numerical Weather Prediction with the WRF Model

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Abstract

Through a collaborative partnership, principally among NCAR, NOAA, DoD, OU/CAPS, FAA, and universities, the U.S. modeling community is developing a next-generation mesoscale model, known as the Weather Research and Forecasting (WRF) model. The goals of the WRF project are to develop an advanced mesoscale forecast and data assimilation system and to accelerate research advances into operations. The model is intended to improve forecast accuracy across scales ranging from cloud to synoptic, with priority emphasis on horizontal grid resolutions of 1-10 kilometers. Numerous real-time forecasting experiments are being conducted to evaluate WRF performance in a variety of forecast applications. In addition, the model is being comprehensively tested for an ensemble approach to be implemented operationally at NCEP. This paper will describe the WRF model, discuss current status of development, and present recent results on the prediction of mesoscale weather systems.

1. Introduction

Over the past two decades we have witnessed significant advances in the development and applications of high-resolution mesoscale models. Mesoscale models with grid resolutions of 1 to 10 km and with advanced physical parameterization are powerful research tools to study various mesoscale weather systems, including topographically forced flows, mesoscale convective systems, hurricanes, and mesoscale frontal structures associated with extratropical cyclones. Real-time prediction using high-resolution mesoscale models has demonstrated considerable skill in predicting local weather, and has facilitated many downstream forecast applications (e.g., hydrological forecasts, regional air quality prediction) (Mass and Kuo, 1998; Mass et al., 2003). Stimulated by the success of mesoscale numerical weather prediction (NWP), many operational centers around the world are actively pursuing the development and operational use of high-resolution nonhydrostatic mesoscale models. With an objective to accelerate transfer of research advances into operation, the U.S. modeling community has embarked on the development of a next-generational mesoscale modeling system, known as the Weather Research and Forecasting (WRF) model. The goal of the WRF project is to develop an advanced mesoscale forecast and data assimilation system that can be used to improve forecast accuracy across scales ranging from cloud to synoptic, with priority emphasis on horizontal grid resolutions of 1-10 kilometers.

The development of the WRF model has been carried out by 15 WRF working groups, through a collaborative partnership. Prototype versions of the WRF model have been released over the past few years (Michalakes et al., 2001; Skamarock et al., 2001). More than 1500 users have downloaded the model for testing and experimentation. Daily real-time prediction is being performed at NCAR, NCEP, U.S. Air Force Weather Agency, NOAA Forecast Systems Laboratory (FSL), National Severe Storm Laboratory (NSSL), and various universities. In addition, the model is being comprehensively tested for an ensemble approach to be implemented operationally at NCEP. For details of the WRF project, please refer to the web site: http://www.wrf-model.org/.

2. Description of the WRF Model

Figure 1 provides a schematic diagram of the WRF model software infrastructure. The WRF design allows for multiple dynamical

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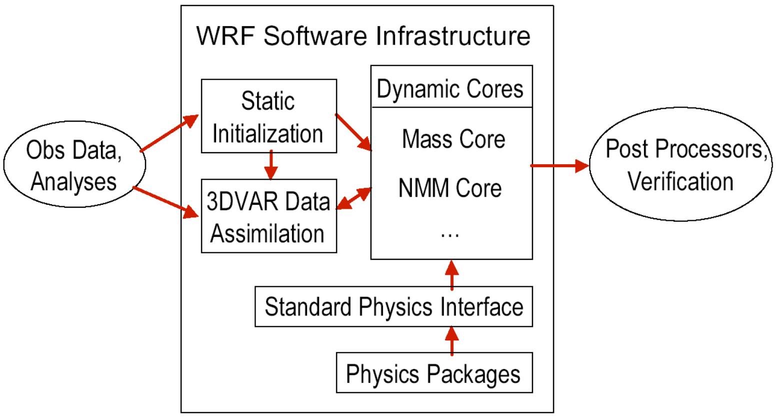

Fig. 1. Schematic diagram of the WRF model software infrastructure.

cores. Dynamical cores using height and mass vertical coordinates were implemented (Skamarock et al., 2001), and after considerable testing the mass coordinate core was selected for further development. The horizontal staggering for the mass core WRF model is an Arakawa-C grid. The WRF model integrates the fully compressible nonhydrostatic equations of motion. It uses a two time level, 3rd order Runge-Kutta (RK3) split-explicit time integration scheme (Wicker and Skamarock, 2002), and a 5th order upwind advection scheme. The model can be initialized with real data or idealized initial conditions. Initialization of WRF can be done through interpolation from analyzed gridded data or through 3DVAR data assimilation. Recently, the NCEP Nonhydrostatic Mesoscale Model (NMM) dynamic core (Janjic et al., 2001) has been added to the WRF framework. Multiple options for physics packages are connected to the model through a standard "plug compatible" interface.

The WRF model software architecture (Michalakes et al., 2001) is highly modular. It uses a single source code approach with plug-compatible modules. Efficient execution over the range of computation platforms available to the WRF user community, from large NWP centers to small groups of university researchers, was a critical requirement in the design and implementation of WRF. The resulting infrastructure is performance-portable over multiple modes of parallelism (shared- and distributed-memory) and processor type (microprocessor and vector). Figure 2 shows performance scaling as the number of processors is increased on a number of platforms in use for NWP today, including the new Cray X1, a vector MPP architecture. At 300 processors, the number of X1 CPUs exactly decomposes the 300 latitudes of the domain, resulting in a dramatic bump in performance. Other results shown are for the SGI Altix and HP Superdome systems (Intel Itanium-2 processors), the Pittsburgh Supercomputing Center's Terascale Computing System (Alpha EV68 processors), the NCAR IBM system (Power4 processors), and a Linux/Pentium-4 system at NOAA/Forecast Systems Laboratory. Older IBM Power3 results are also shown. The fastest runs shown in figure (Cray and Pittsburgh TCS) represent four minute run times for a 48 forecast on this domain. The latest release of WRF, version 2.0, includes 2-way interacting nests. The performance overhead for nesting (not shown in the figure) is between 5 and 8 percent on 64 processors (IBM), well within the original requirement of no more than 15 percent penalty for nesting.

WRF is a target application within the current NASA-funded Earth System Modeling Framework (ESMF) effort, and WRF developers are working with ESMF providing input on ESMF design and implementation and on integrating aspects of the WRF and ESMF as ESMF becomes available. WRF 2.0 includes the ESMF time manager. The top level of the WRF model is also compatible as a component in multi-model simulations using the ESMF coupling superstructure.

3. Real-time and Retrospective Forecasting with WRF

Real-time forecasting is an important mean for testing and evaluating models. Through daily examination of model

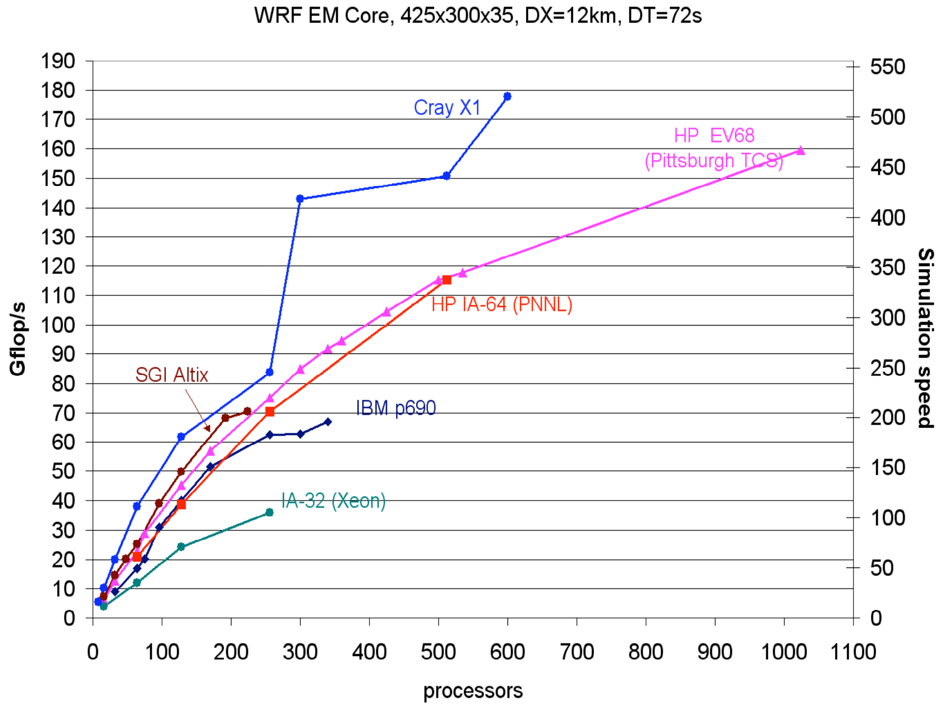

Fig. 2. Computational performance as a function of number of processors running a 12km CONUS benchmark domain. Computational time only; I/O and initialization time not included.

forecasts, we can assess the robustness of the model, understand its behavior, and compare its performance with other models. A real-time forecasting system also provides a useful testbed for evaluating new physical parameterization schemes or new model initialization methods. Several real-time forecasting experiments are currently being conducted to evaluate WRF performance in a variety of forecast applications. For example, the Mesoscale and Microscale Meteorology (MMM) Division of NCAR is routinely running the mass-core WRF model at 10 km and 22 km resolution over the continental U.S. In support of field operations in BAMEX (Bow-Echo and Mesoscale Convective Vortex Experiment; Davis et al., 2003), the NCAR MMM Division produced real-time forecasts using a 4-km WRF model during the period of 13 May to 9 July 2003. Examples of WRF real-time BAMEX forecasts at different resolution, and a comparison with the radar observations are shown in Fig. 3. Done et al. (2003) performed an evaluation of WRF BAMEX forecasts. They found that the 4-km WRF model with explicit parameterization of convection possessed considerable skills in predicting the number of mesoscale convective systems and degree of convective organization. WRF forecasts on the 10-km grid, using parameterized convection, provided similar guidance about precipitation location, but offered little information concerning convective structure. The field forecasters have found the BAMEX 4-km WRF forecasts to be extremely valuable in providing guidance on forecasting of mesoscale convective systems. With the success of high-resolution WRF forecasts and due to popular demand, several high-resolution, real-time forecasts are being run for the 2004 spring and summer seasons. The MMM Division of NCAR is performing another season of 4-km WRF forecast from 29 April through 31 July 2004, initialized from the 40-km ETA analysis. The University of Oklahoma is performing 4-km WRF forecasts initialized from ARPS Data Analysis System (ADAS), and NCEP is running a 5-km WRF with NMM core. These forecasts are available on the web and are being compared in real-time.

In order to determine the initial operational capability (IOC) over high-resolution domains at NCEP for operational use of WRF, NCAR, NCEP, FSL and AFWA are collaborating on retrospective testing of WRF. These retrospective testing include 8 runs (with different model configurations and physics) for 30 days in four seasons, including: (i) August 2002 over Central and Western U.S., (ii) October 2002 over Alaska and Eastern U.S., (iii) February 2003 over Western and Eastern U.S., and (iv) May 2003

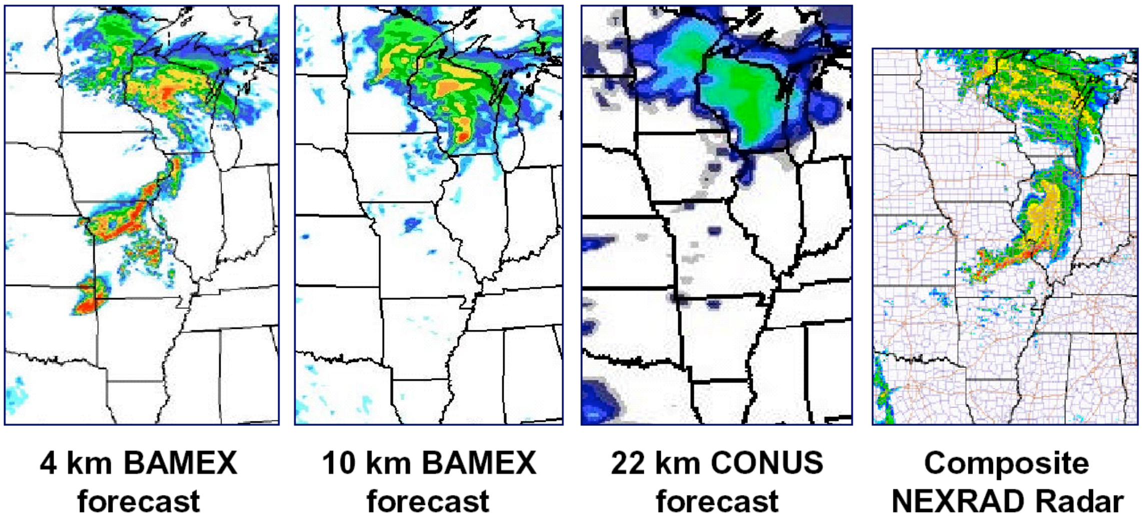

Fig. 3. Comparison of 12-h forecasts by the WRF model at 4-km, 10km, and 22-km grid resolution with NEXRAD observations, valid at 1200 UTC 10 June 2003.

over Central and Eastern U.S. Analysis of these retrospective runs will shed light on what configuration will provide the best mesoscale ensemble for operational forecasting with WRF.

4. Community WRF Release

The WRF model provides a focal point and common modeling framework for the research and operational NWP communities to collaborate on model development and research and forecasting applications. The early versions of the WRF model have already demonstrated considerable skill in predicting mesoscale weather systems. The WRF model V2.0 has now been released to the community. This version includes 1-way and 2-way nesting, with multiple domains and any integer ratio for real-data forecasting and idealized simulations. Several new physics packages have been added, including new land-surface models, new planetary boundary layer models, new microphysics, new cumulus convective parameterization, as well as many new utility programs, which make it easier for users to perform WRF simulations. This release contains a subset of the overall WRF code that is being maintained and supported by MMM Division of NCAR. Other components of the WRF system may be supported for community use in the future, depending on the interests and resources of other organizations.

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